Dynamics of Droplet-Droplet and Droplet-Film Collision

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The physical phenomena of droplet-droplet and droplet-film collision in the head-on orientation were studied experimentally and computationally, with emphasis on the transition between bouncing and merging of the liquid surfaces. Experimentally, the droplets (~300 μm diameter) were generated using the ink-jet printing technique, and imaged using stroboscopy and high-speed cine-photography for the droplet-droplet and droplet-film collision events respectively. Computationally, the collision event was simulated using the front-tracking technique.

For the study of droplet-droplet collision, the instant of merging was experimentally determined and then used as an input in the computational simulation of the entire collision event. The simulation identified the differences between collision and merging at small and large Weber numbers, and satisfactorily described the dynamics of the inter-droplet gap including the role of the van der Waals force in effecting surface rupture.

For the study of droplet-film collision, extensive experimental mapping showed that the collision dynamics is primarily affected by the droplet Weber number (*We*) and the film thickness scaled by the droplet radius (*H*), that while droplet absorption by the film is facilitated with increasing droplet Weber number, the boundary of transition is punctuated by an absorption peninsula, in the *We-H* space, within which absorption is facilitated for smaller Weber numbers. Results from computation simulation revealed the essential dependence of the collision dynamics on the restraining nature of the solid surface, the energy exchange between the droplet and the film, and the coherent motion of the gas-liquid interfaces. Partial absorption with the emission of a secondary droplet of smaller size was also observed and explained.

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C. K. Law, Princeton University

International Symposium on
Energy Conversion Fundamentals
June 21-25, 2004, Istanbul, Turkey

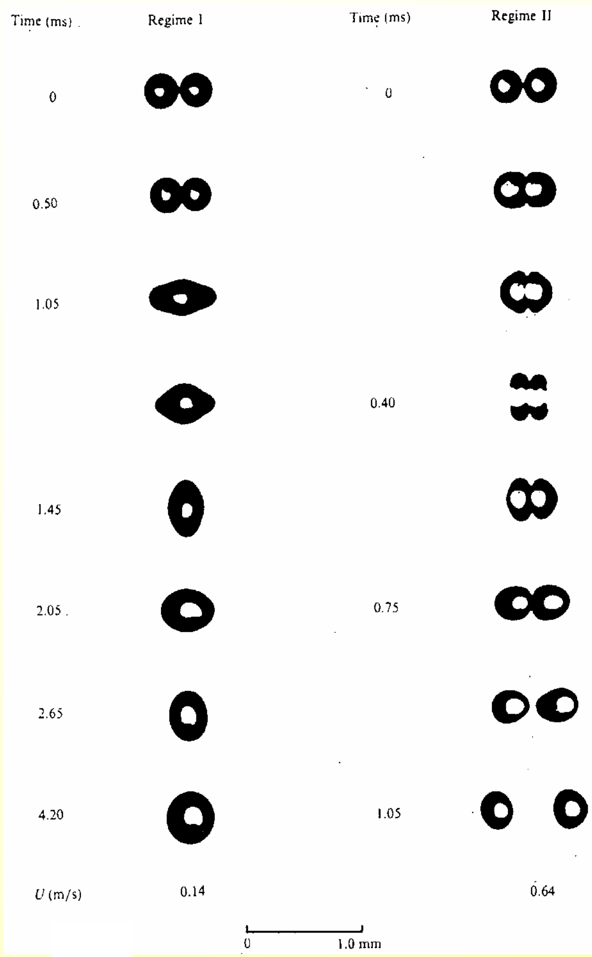
Practical Relevance

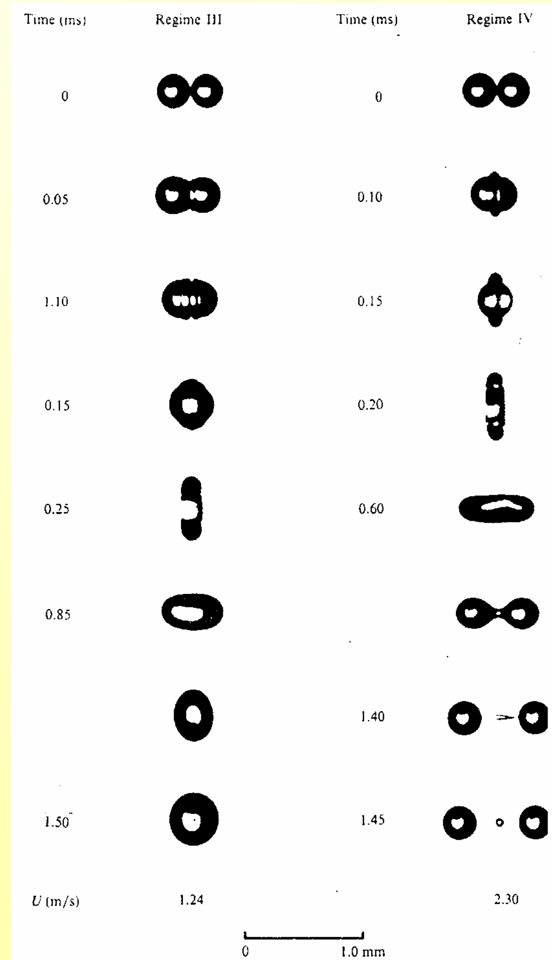
- Droplet-droplet collision:
  - Spray processes
  - Rain drop formation
  - Model for nuclear fusion
- Droplet-surface collision:
  - Spray impingement on surface of combustion chamber
  - Raindrop interaction with ocean and soil
  - Meteorite impaction
  - Ink-jet printing
  - Spray-painting/coating

Fundamental Interests

- Dynamics of deformable bodies
- Large deformation implies nonlinear dynamics
- Many decades of length scales:
  - Droplet size: $10 \sim 10^3$ μm
  - Molecular force distance: 10^{-2} μm
- Wide range of physical regimes:
  - Continuum flows
  - Rarefied flows
  - van der Waals force
- Computationally & experimentally challenging
- Description of state of merging

Dynamics of Droplet-Droplet Collision





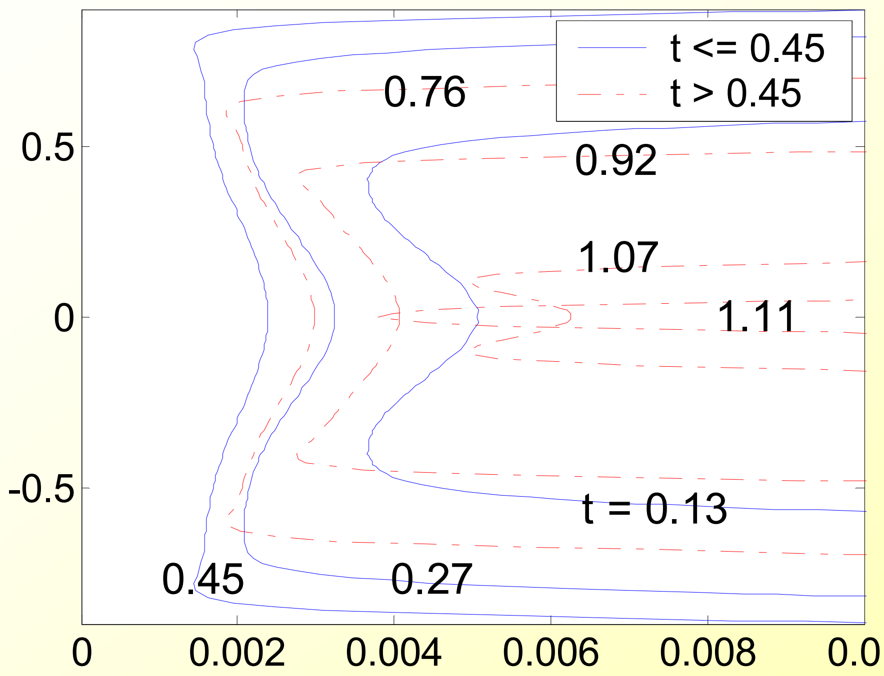
Computational Simulation

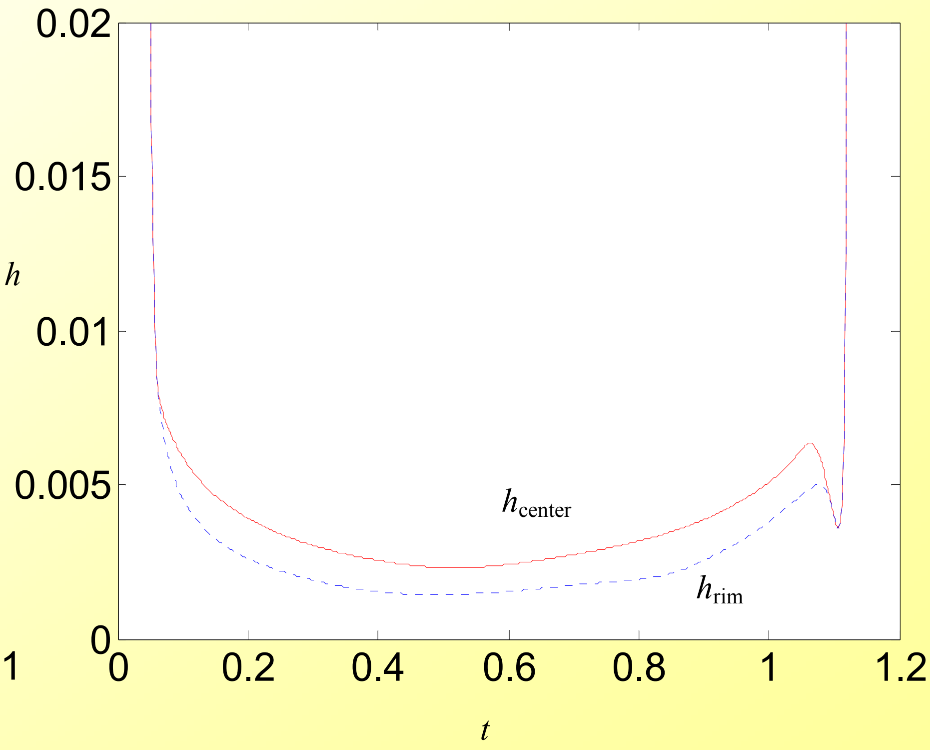
- Front tracking method of Tryggvason & immersed boundary method of Peskin

- Continuum formulation

$$\frac{\partial(\rho\mathbf{V})}{\partial t}+\nabla\cdot\left(\rho\mathbf{V}\mathbf{V}\right)=-\nabla p+\mathbf{g}+\nabla\cdot\frac{1}{Re}\left(\nabla\mathbf{V}+\nabla\mathbf{V}^{\mathrm{T}}\right)-\frac{8}{We}\int_{\Delta s}\kappa\mathbf{n}\,\delta(\mathbf{r}-\mathbf{r}_{\mathrm{f}})\,da$$

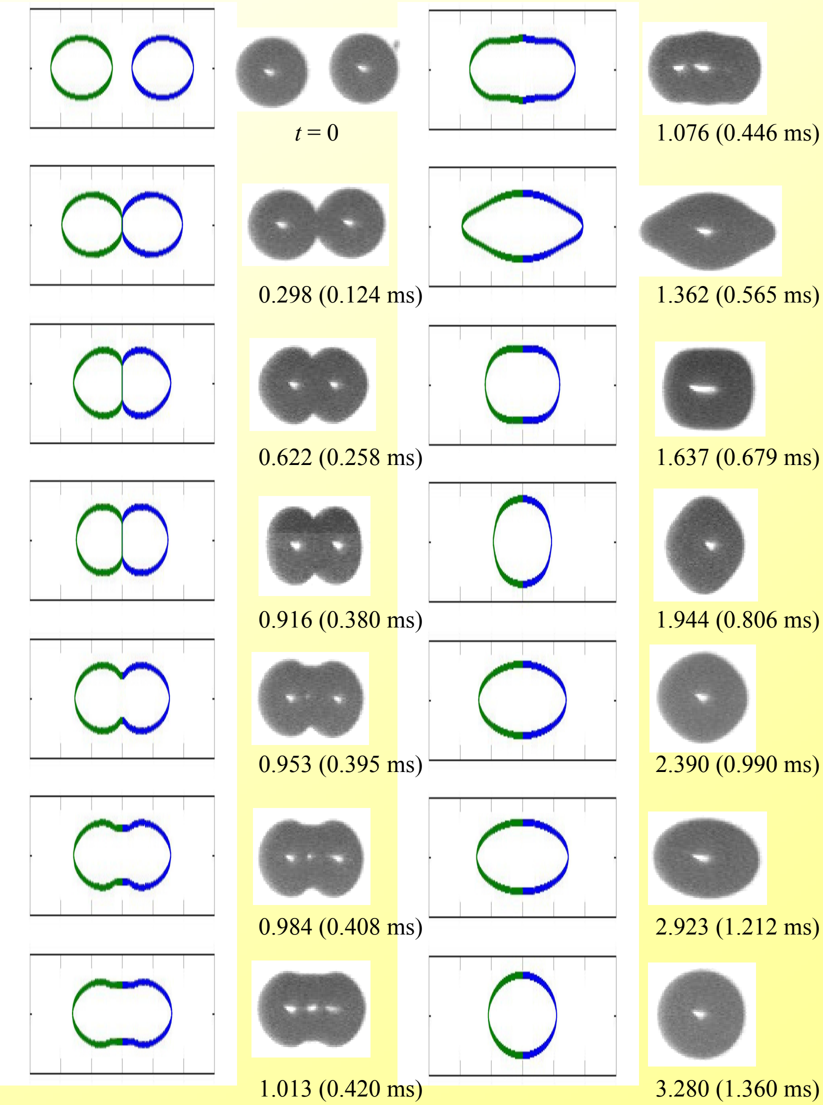
Dynamics of Colliding Interfaces



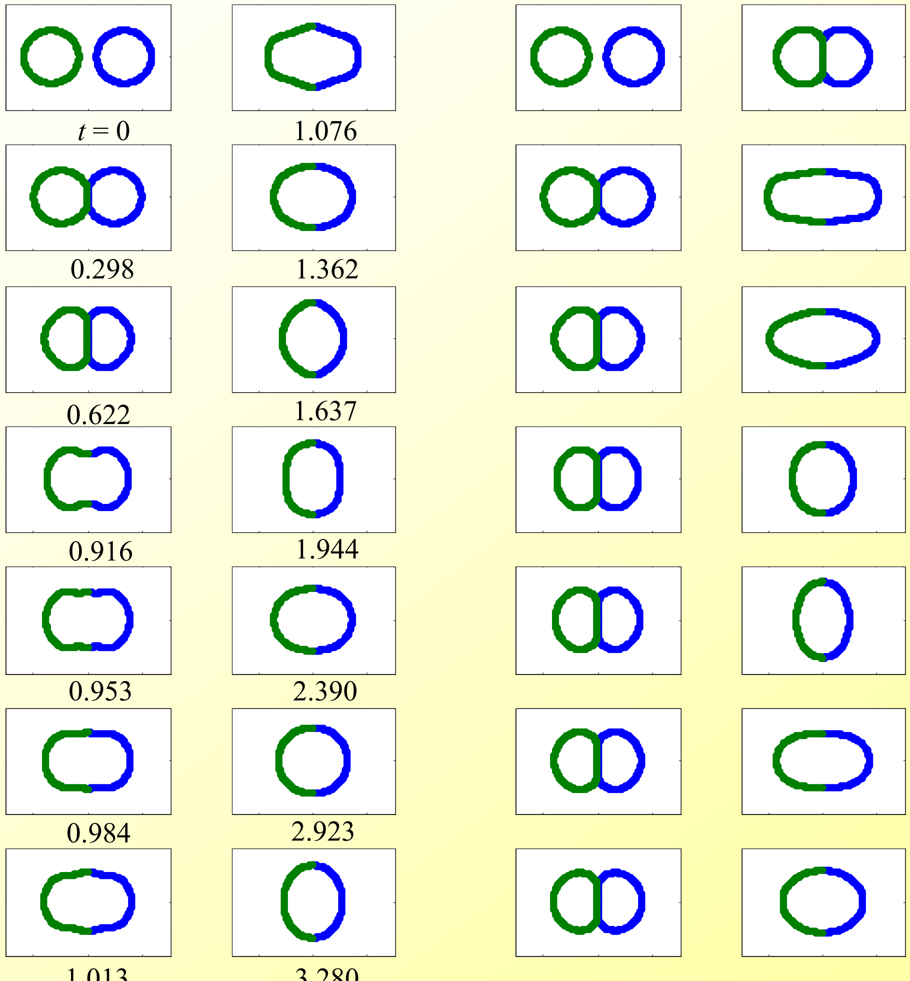


Matched Instant of Merging

- Identify experimental instant of curvature reversal of interface cusp as state of surface rupture
- Use this instant in simulation
- Close agreement with experimental images



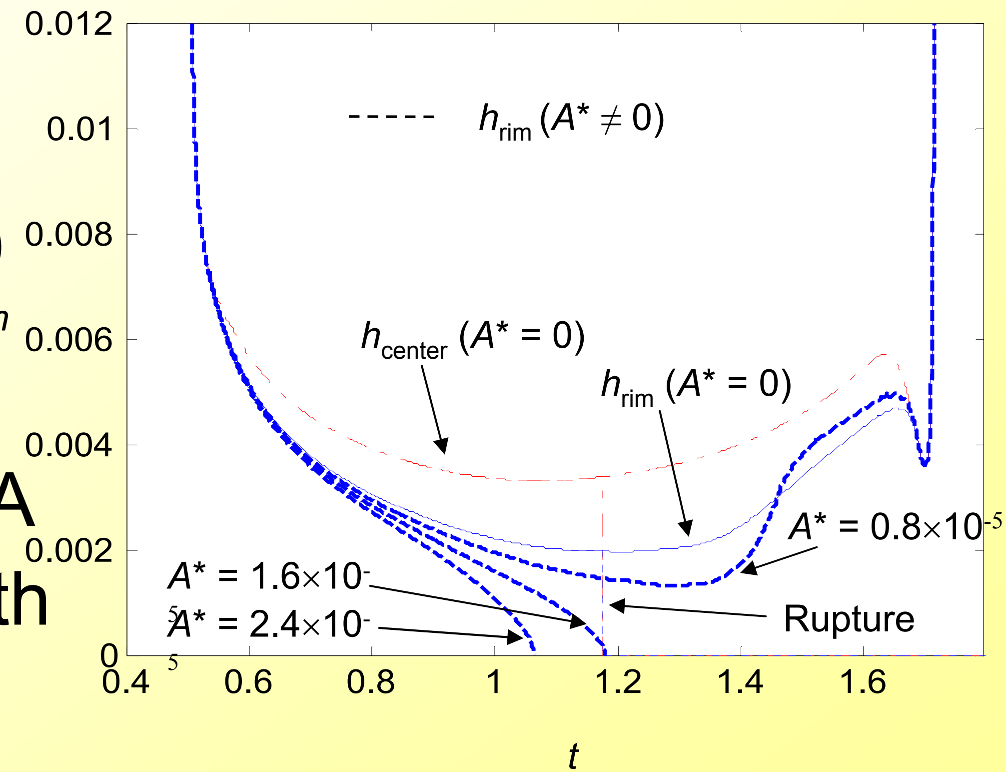
Mis-Matched Instants of Merging



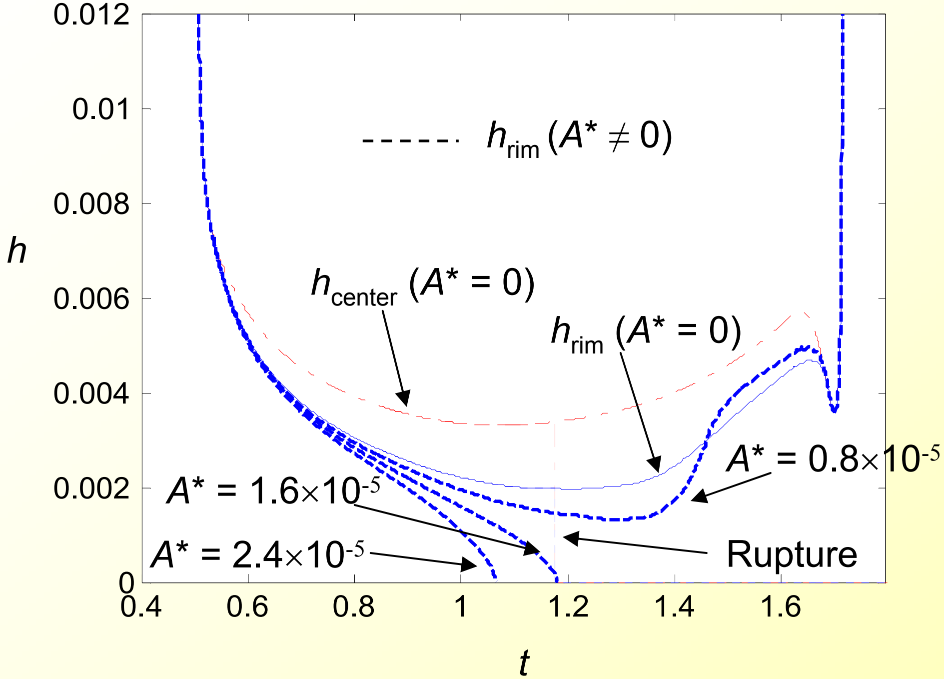
- Advanced rupture
- Delayed rupture

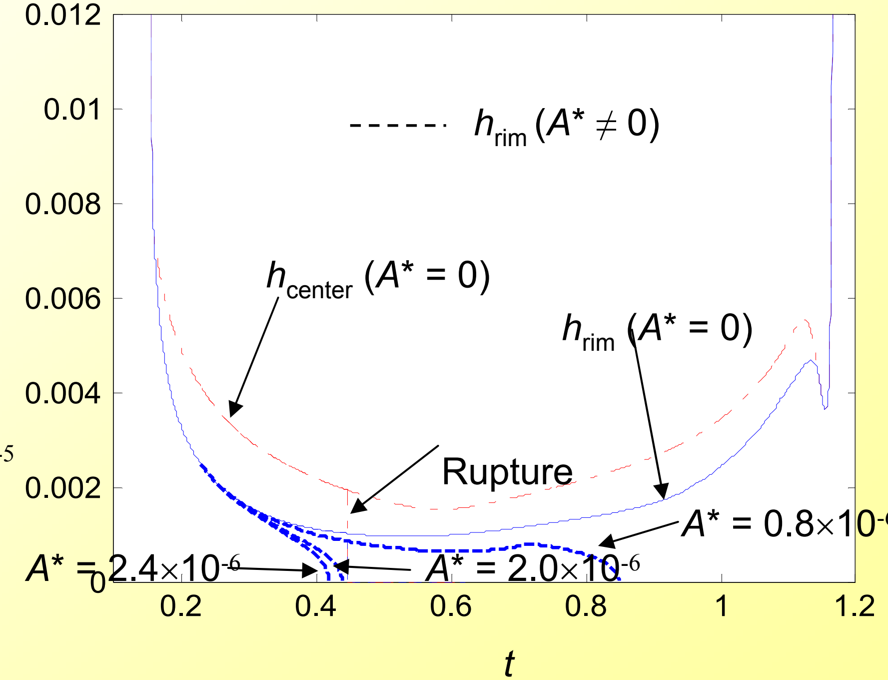
Surface Rupture Induced by Molecular Force (1/3)

- To effect surface rupture, add van der Waals force in formulation: $A/(6\pi\delta^3)$
- Simulation shows divergence of interface for certain A
- Adjust A to agree with empirical instant of rupture



Surface Rupture Induced by Molecular Force (2/3)





- Soft merging occurs late in collision, at rim
- Hard merging occurs early in collision, at rim

Surface Rupture Induced by Molecular Force (3/3)

- Augmented Hamaker constant is 10^3 to 10^6 larger than the real one
- Implying the interfacial gap width from simulation is one to two orders too large
- Consistent with:

Simulated gap width ~ 10^{-1} μm

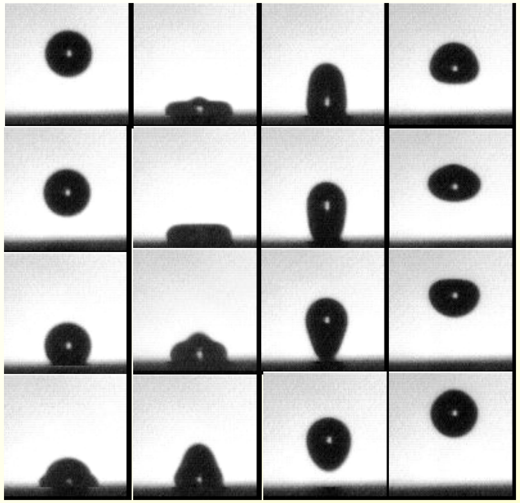
van der Waals force range ~ 10^{-3} - 10^{-2} μm

Missing Physics

- Additional physics needed so that the interface can reach the range of the molecular force
- Need rarefied flow treatment
- Need variable density treatment
- Computationally challenging
- Possibly described through analysis

Dynamics of Droplet-Film Collision

(Thin film)



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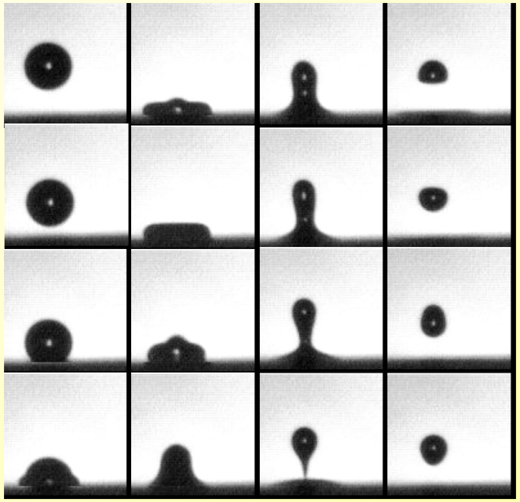

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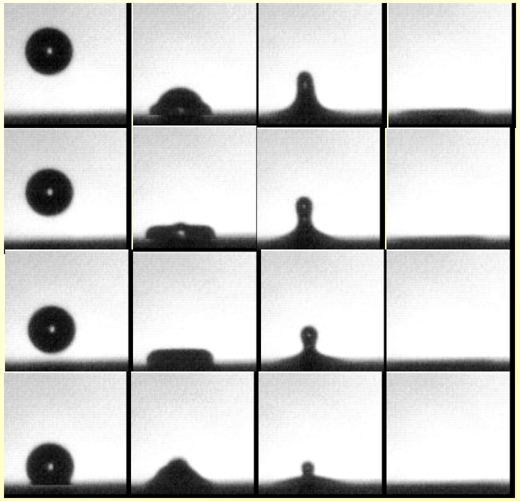
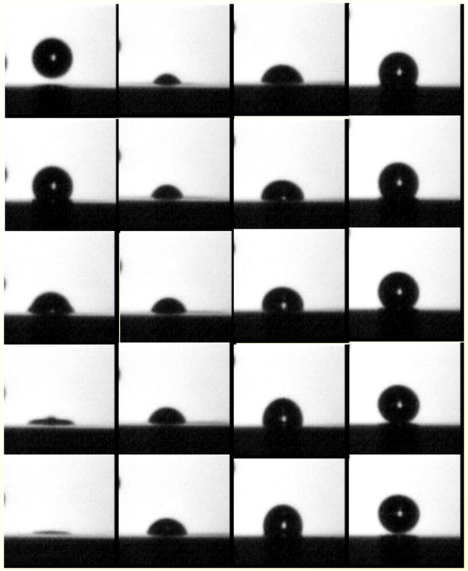


(c)

- (a) Bouncing
- (b) Partial absorption
- (c) Total absorption

Dynamics of Droplet-Film Collision

(Thick film)



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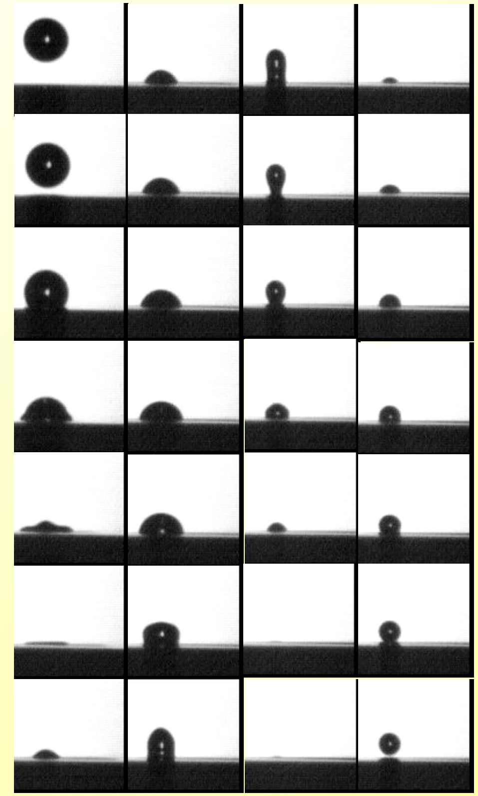

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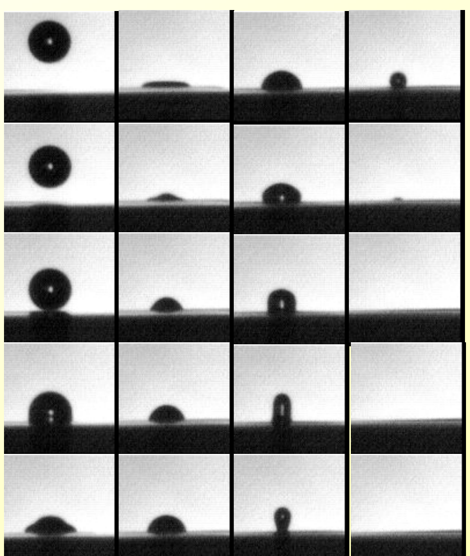
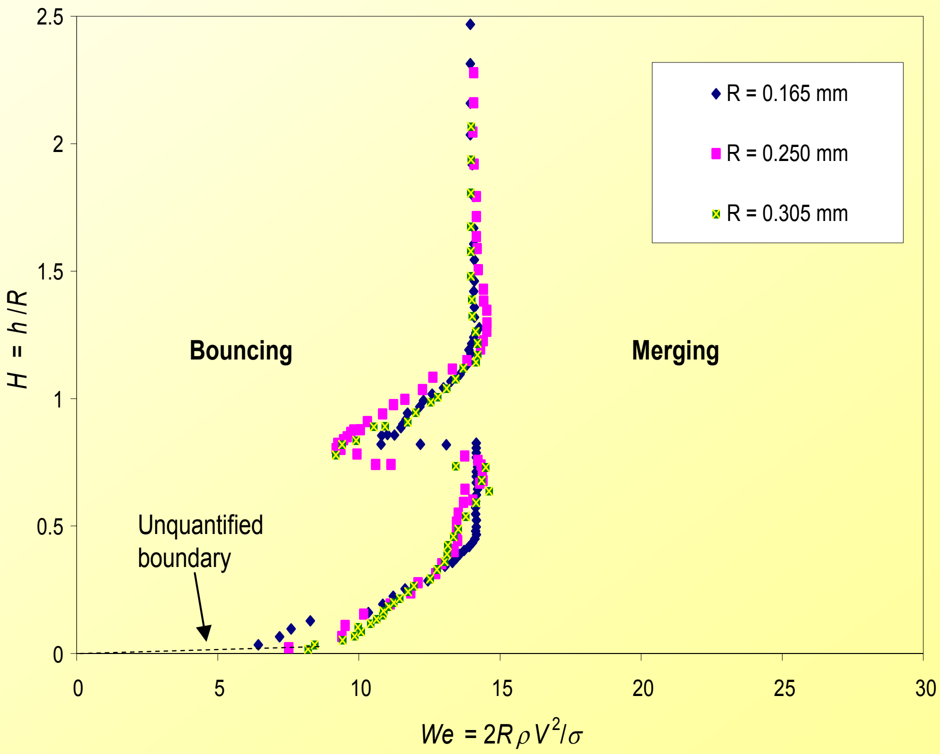


(c)

- (a) Bouncing
- (b) Partial absorption
- (c) Total absorption

Regime Diagram of Droplet-Film Collision

- Controlling parameters: Weber number & film thickness (H=h/R)
- Existence of merging peninsula around H≈1
- Existence of triple reversal in absorption & bouncing with increasing H



Factors Affecting Bouncing vs Absorption

- Solid surface restrains droplet motion
- Impact inertia narrows interfacial gap
- Droplet flattening increases resistance
- Droplet deformation increases viscous loss
- Energy transfer to film
- Oscillatory resonance around $H \approx 1$

Summary

- Instant of droplet merging can be empirically determined and used to simulate complete droplet collision sequence
- Surface rupture can be induced through an augmented van der Waals force
- Proper description of interfacial dynamics, allowing for rarefied flow and variable density, is essential
- For droplet-film collision, existence of merging peninsula around $H \approx 1$